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TRAJECTORY ANALYSIS OF THE G-11 FAMILY OF CLUSTERED PARACHUTES TO DETERMINE MINIMUM ALTITUDE

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The U.S. Air Force is interested in determining the minimum altitude at which an aircraft can approach a drop zone and deploy an airdrop system to deliver cargo without its becoming damaged. Lower altitudes will reduce the exposure of aircraft to hostile fire, but being too low will result in the destruction of the cargo. The objective of this report is to determine the minimum altitude at which the cargo may be safely delivered. This was accomplished by analyzing trajectory data for airdrop systems using the G-11 parachute. It was found that the first point (time) at which cargo can be safely landed occurs when the cargo velocity reaches its first minimum total velocity, coincident with the first maximum backswing orientation of the system. This criterion was used to determine the statistical mean of the altitude loss. The importance of variability is discussed as it relates to the determination of a safety factor.

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Preface

The U.S. Air Force is interested in dropping cargo from the lowest possible altitude in order to minimize exposure of aircraft to hostile fire. To support a rational determination of minimum altitude, trajectory data was acquired from the Airborne and Special Operations Test Directorate, Operational Test and Evaluation Command (OPTEC), at Fort Bragg, North Carolina for a wide range of airdrop systems. This included clusters of from one to eight parachutes.

An assessment of the risk of damaging cargo when it lands at various orientations and velocities showed that the earliest point or time that the cargo can be safely landed is when it reaches its **first minimum total velocity.**

By calculating the system vertical angle, it was found that the first minimum total velocity of the cargo always occurs at (or just prior to) the **first maximum backswing** orientation of the system.

Based upon these findings, the altitude loss of the cargo from extraction (exit) to occurrence of the first minimum total velocity was used to statistically determine the minimum altitude (separate report).

Sources of error and variability are discussed, not only as they relate to the accuracy of the statistical mean of altitude loss, but also to substantiate the need for a safety factor to be added to this statistical mean. Only in this way can an acceptable performance reliability for the low-velocity airdrop method be maintained.

Various recommendations are made to improve airdrop:

- continue to develop the parachute database
- validate the new method of determining system vertical
- understand the effects of wind upon variability and reliability
- understand the effects of wind shear upon accuracy
- investigate the accuracy of weather balloons

TRAJECTORY ANALYSIS OF THE G-11 FAMILY OF CLUSTERED PARACHUTES TO DETERMINE MINIMUM ALTITUDE

Introduction

Purpose

The low-velocity airdrop method delivers cargo from fixed-wing aircraft to the ground, using parachutes to extract the cargo from the rear of the aircraft and decelerate it to a safe speed for landing. During this process the axis of the system, initially horizontal, swings like a pendulum to a vertical position.

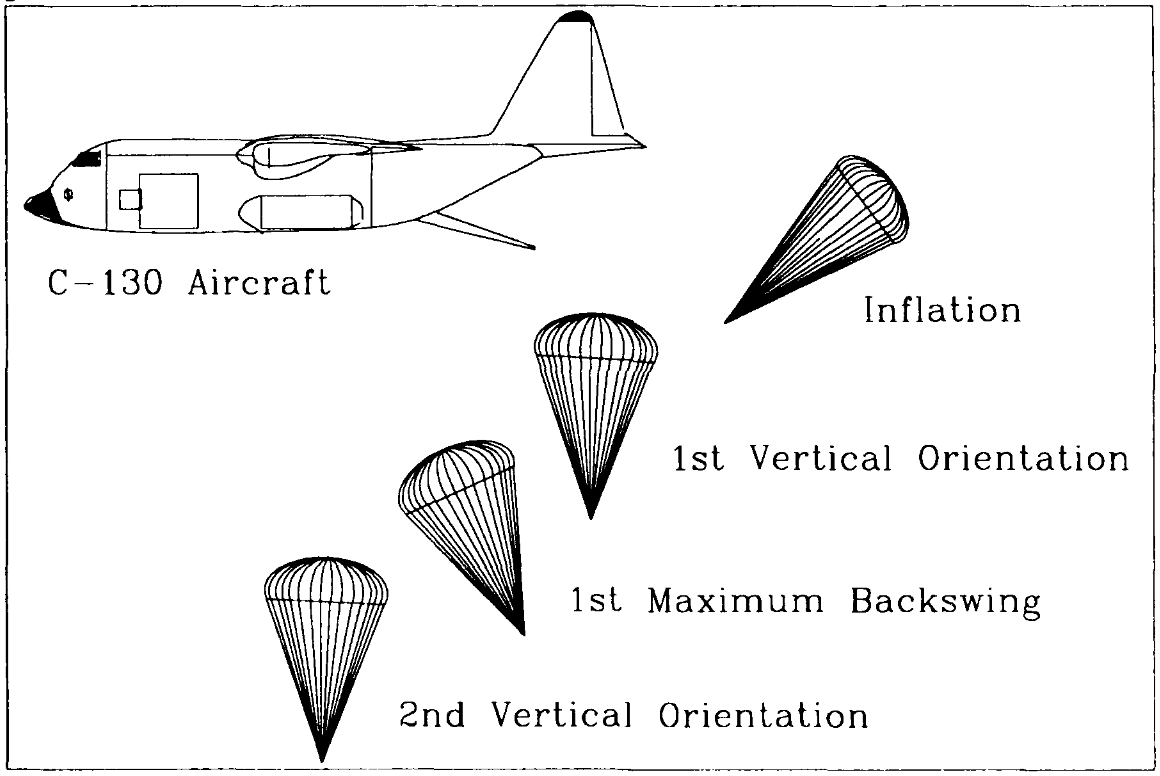

Figure 1: Low-velocity Airdrop Method

Delivery of a wide range of cargo size and weight is achieved by varying the number of parachutes used. Such ensembles of parachutes are called **clusters.**

The purpose of this report is to describe the methods used to determine the minimum altitude for airdrop systems deployed using the "low-velocity" method. The family of G-11 systems comprised of single or clustered G-11 parachutes (100 foot nominal

diameter), presently used to deliver cargo of various weights, was investigated.*

The **minimum altitude** is the lowest altitude at which an aircraft can approach a drop zone and deploy an airdrop system to deliver cargo without its being damaged. It is of particular interest to the U.S. Air Force because a lower altitude during approach will reduce the exposure of aircraft to hostile fire. Being too low, however, will result in the destruction of the cargo being delivered.

This report is an attempt to find middle ground. It describes previous and new methods for determining the minimum altitude for each of the existing low-velocity airdrop systems. Considerable attention is paid to the sources of error and the variability which is embedded in the trajectory data used to determine the minimum altitude.

Variability is the basis for assigning reliability factors to the average minimum altitude, determined for each family of low-velocity airdrop systems. An understanding of variability will help focus future efforts in improving system reliability and accuracy.

Previous Definitions

The **Minimum Altitude** has traditionally been defined by the airdrop community as the vertical distance between the altitude of the cargo at the time it is extracted from the aircraft, and its altitude at the time the system reaches "equilibrium," a term defined below.**

Vertical Angle has been traditionally defined by means of the system axis, a line connecting the center of mass of the cargo to the geometric center of the canopy. The vertical angle is, then, the angle between the system axis and the vertical line radiating from the center of the earth.***

Equilibrium has been defined as the state of the system (parachute and cargo) as the cargo nears terminal velocity and the system reaches a vertical orientation.[1] Since airdrop

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* Each G-11 parachute typically can deliver up to approximately 5000 pounds of cargo.

** A safety margin must be added to account for the variability in performance due to systemic effects (reefing, timers, etc.) and environmental effects (wind, temperature, etc.) which prevail at the time of the drop. This is referred to as the "reliability factor."

*** In the past the system axis was determined by analyzing films which record the spatial position of both the cargo and the canopy. In analyzing these films a line is drawn from the center of gravity of the cargo to the geometric center (centroid) of the parachute from which it is suspended. The location of the centroid of the canopy is visually estimated. For clusters of parachutes, the same method can result in considerable error since the location of the centroid of a cluster of canopies is not at all clear.

systems typically do not reach system terminal velocity until sometime after the system reaches its first vertical orientation, "equilibrium" has traditionally been defined as the point where the system reaches its **second vertical** orientation.[2]

Altitude Loss is the distance between the altitude of the cargo at the time of extraction (exit), and the altitude of the cargo at a particular later time of interest.

Present Low-Velocity Airdrop Method

The following summarizes the low-velocity airdrop method:

Extraction

The cargo is horizontally extracted from the rear of the aircraft, during which time the line connecting the center of gravity of the cargo to the geometric center of the extracting parachute is nearly horizontal, i.e. the system vertical angle is approximately 90 degrees at this time.

Inflation

The canopies inflate in a controlled manner, such that they are not damaged during deceleration of the cargo.

Rotation

During the inflation phase, the rotation of the system is relatively slow when the trajectory can be described as "ballistic." After opening shock occurs, the angular velocity of the system axis increases, and reaches a maximum as the system passes through its first vertical orientation. It then undergoes an angular deceleration until it arrives at the maximum backswing position.

Oscillation

After the system reaches the maximum backswing orientation, it reverses direction and continues to display pitching oscillations about the vertical, similar to the motion of a pendulum. The magnitude of these pitching oscillations may gradually decrease, depending upon the amount of systemic (inherent) damping. Each family of airdrop systems displays its own characteristic damping.*

Since there is a need to minimize the altitude of the aircraft, it will in general be necessary to land the cargo before pitching oscillations have dampened out.

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* The smaller clusters (1-3) display little, if any damping. The greater the number of parachutes in a cluster, the greater the damping effect upon pitching oscillations.

Effective System Vertical

This report also describes the results of analyzing parachute trajectories without recourse to the previously described method of visually estimating the effective centroid of the canopies. See previous definitions, system vertical, on page 2.

Instead, the **effective** system vertical angle was computed using an equation derived from first principles (discussed later in this report). It supports an objective method for determining the system vertical angle, an estimate of the system orientation. This has proved to be an invaluable tool in improving the understanding of parachute pitching oscillations.

Description of Trajectory Data

The trajectory data was acquired by tracking the position of the cargo store using at least two earth-fixed optical cameras and using triangulation to compute the spatial position of the cargo store as a function of time, in earth-fixed (X-Y-Z) coordinates.

The data is received as a file (ASCII format), which presents the data in tabular form by displaying the position, velocity, and acceleration, along the three earth-fixed coordinates as a function of time. Only the position is actually measured, i.e. velocity and acceleration is derived via differentiation.

The X-Axis of the trajectory data represents the direction (line of flight) of the aircraft just before the cargo was extracted. This is done by aligning (rotating) the spatial trajectory data so that the line of flight of the aircraft just prior to extraction is aligned with the X-Axis.*

In summary, trajectory data is based upon the measurement of the spatial position of the cargo store from the time it has been extracted until it lands. The X-Axis represents the horizontal direction (line of flight) of the aircraft just prior to extraction. The Y-Axis represents the horizontal direction of the cargo transverse to the the X-Axis, and the Z-Axis represents the altitude of the cargo store with respect to mean sea level.

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* When there are winds aloft, the line of flight (with respect to earth) will not be in alignment with the axis of the aircraft. The aircraft will be observed to be "crabbing." Hence the initial (total) velocity of the cargo store (with respect to earth) will generally differ from its velocity with respect to the air.

Method

Trajectory data was used to assess the following significant issues impacting airdrop system performance.

Risk

For all systems, the horizontal velocity of the cargo was found to be high as the system reaches a vertical orientation for the first time. Such a high velocity precludes landing the cargo at the first vertical orientation of the system. This is an unavoidable consequence of the present method of extracting cargo from the rear of a horizontally moving aircraft.

But at what point, after the system reaches its first vertical orientation, can the cargo first be landed safely?

Trade-Offs

The more conservative approach will require the Air Force to approach the drop zone at a higher altitude, increasing its exposure to hostile fire. Conversely, being too low can result in damage or destruction of the cargo being delivered.

Survivability

A brief study of the survivability of the cargo which lands during the oscillation phase (at various angles and velocities) has shown that the survivability function fluctuates with time.*

There is then, a tradeoff between the advantage of landing the cargo when the system is vertical and the alternative of landing it at the maximum backswing orientation. In the first case the cargo will land at high horizontal velocity exposing the load to the danger of rollover or transverse shear damage; but, the orientation does have the best potential for dissipating energy through the paper honeycomb energy pads. In the second case the total velocity of the cargo is low (when the horizontal component is near zero) but its orientation is such as to reduce the effectiveness of the paper honeycomb to uniformly dissipate kinetic energy. This less than optimum performance of the paper honeycomb can subject the cargo to higher shock levels.

Controllability

Even if there was agreement on a preferred orientation at ground impact, airdrop systems cannot be controlled to land at that particular preferred orientation. Studies have shown that the

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* When the system is vertical the horizontal velocity is a maximum; whereas, wnen the system is at its maximum backswing orientation the horizontal velocity is nearly (depending upon wind conditions) zero.

time from extraction to first vertical cannot be predicted more accurately than to within plus or minus several seconds.*

It was decided that when the maximum backswing angle is less than about 25 degrees, the total kinetic energy of the cargo is the best predictor of damage to the cargo store.

Total Velocity

Since kinetic energy of an object is proportional to the square of the total velocity, the total velocity was examined. It was observed that ALL systems display a consistent pattern of behavior: the total velocity of the cargo rapidly reaches a minimum value, after which it continues to oscillate about a mean value, with the maximum (oscillatory) value occurring at the second vertical.

The plot of the total velocity of the cargo versus altitude loss was chosen as the basis for further analysis of the G-11 family of airdrop systems covered in this study. The following graph is typical. It displays the total velocity of the cargo, and the drop time from extraction (exit) vs altitude loss (drop).

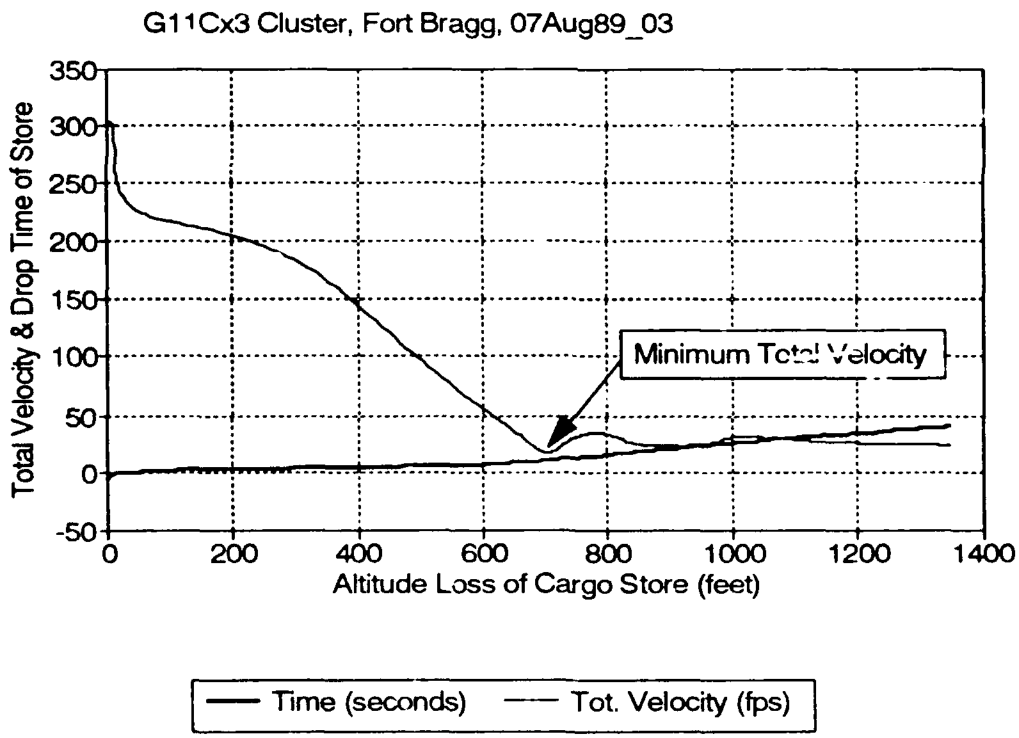

Figure 2: Total Velocity and Elapsed Time versus Altitude

* The standard deviation of the time to reach first vertical was found to be at least +/- 1 second for a single canopy system, and approximately +/- 3 seconds for a cluster of 8 canopies. This time variance, corresponds to an altitude variance of from 24 to 65 feet, and a system orientation variance of from +/- 1/10th to 1/4 of an oscillation cycle, where 1 one (full) oscillation cycle would return the system to essentially the same orientation.

To determine the time and altitude loss at the first minimum total velocity of the cargo, the following graph, a magnified version of the previous graph, was used extensively:

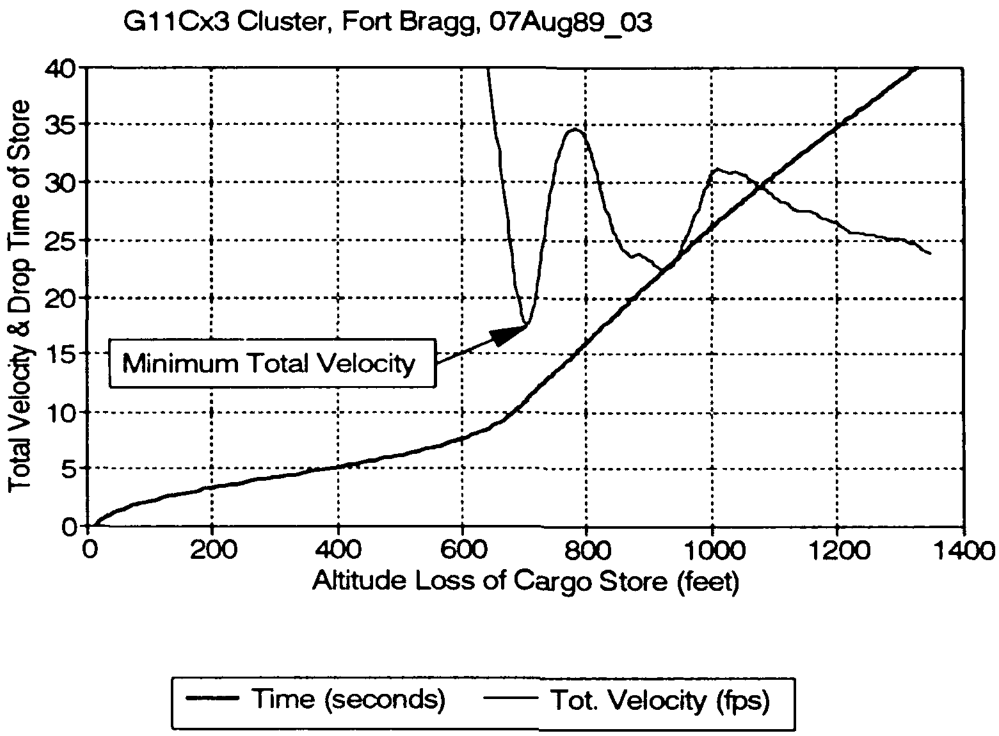

Figure 3: *Magnified Total Velocity and Elapsed Time*

Of particular note is the sharpness of the minimum velocity point. Preceding this point, the total velocity can be seen to be decreasing rapidly. Since the kinetic energy (proportional to velocity squared) is the best predictor of cargo damage, landing the cargo just a short time before the minimum total velocity point will likely result in damage or destruction.

Calculation of System Vertical Angle

Subsequent to initial studies, equations were derived to calculate the total system drag, and the effective system vertical angle.

These equations are based upon the assumption that the net force generated by the canopy is the predominant force acting upon the cargo and that the direction of this net force (with respect to vertical) can be calculated from trajectory data.

A single parachute system is comprised of a canopy and a cargo which are connected together by suspension and riser lines. The net force which acts upon the cargo can be calculated using Newton's Laws of motion because after opening shock has occurred the aerodynamic drag of the cargo is small. This can be shown by calculating the drag force upon the small cargo platform based upon the velocity which is known from trajectory data.

Ignoring the aerodynamic force upon the cargo allows one to presume that the measured acceleration of the cargo is due to only two forces: gravity and the drag produced by the canopy. These two forces can be compared to determine the direction of the force applied to the cargo by the canopy.

The acceleration of the cargo (calculated from spatial position data) can be used to determine the total force per unit mass (specific force) which acts upon the cargo in the X/Z plane:

$$D_t/M_s = [(d^2x_s/dt^2)^2+(g_e+d^2z_s/dt^2)^2]^{1/2} \qquad (1)$$

where:

D_t = total aerodynamic drag acting on the cargo
M_s = the mass of the cargo (store)
x_s = the position of the cargo along X-Axis
z_s = the position of the cargo along Z-Axis
g_e = the gravitational constant on earth

The direction of this force with respect to the Z-Axis may also be calculated as follows:

$$\mathrm{Theta} = \mathrm{Tan}^{-1}[-(d^2x_s/dt^2)/(g_e+d^2z_s/dt^2)] \qquad (2)$$

The effective system vertical angle in the Y/Z plane can also be calculated to study the parachute phenomenon known as "coning."

The effective direction of the force, calculated here, is not the conventional direction from the center of gravity of the cargo to the centroid of the canopy; but rather the direction of the net force imposed upon the cargo by the canopy(s). This definition of the net force generated by a single canopy defines an axis which passes through the center of pressure within the canopy, and not in general through the conventional center (vent) of the canopy. For a system of clusters, the effective direction is the result of all canopies acting at different angles upon the confluence point of the system. Such a definition recognizes that the location of the center of pressure within a canopy, or caused by the a cluster of canopies, is dynamic and associated with small distortions or realignments of the canopy(s) during oscillations. These distortions or realignments are typically small so that the difference between the previous definition of the system vertical angle and the "effective" system vertical will generally also be small.

First Maximum Backswing

Using equation (2), it was found that the first minimum total velocity always occurs at, or slightly before, the first maximum backswing. This relationship is shown in the following graph of a cluster of three parachutes:

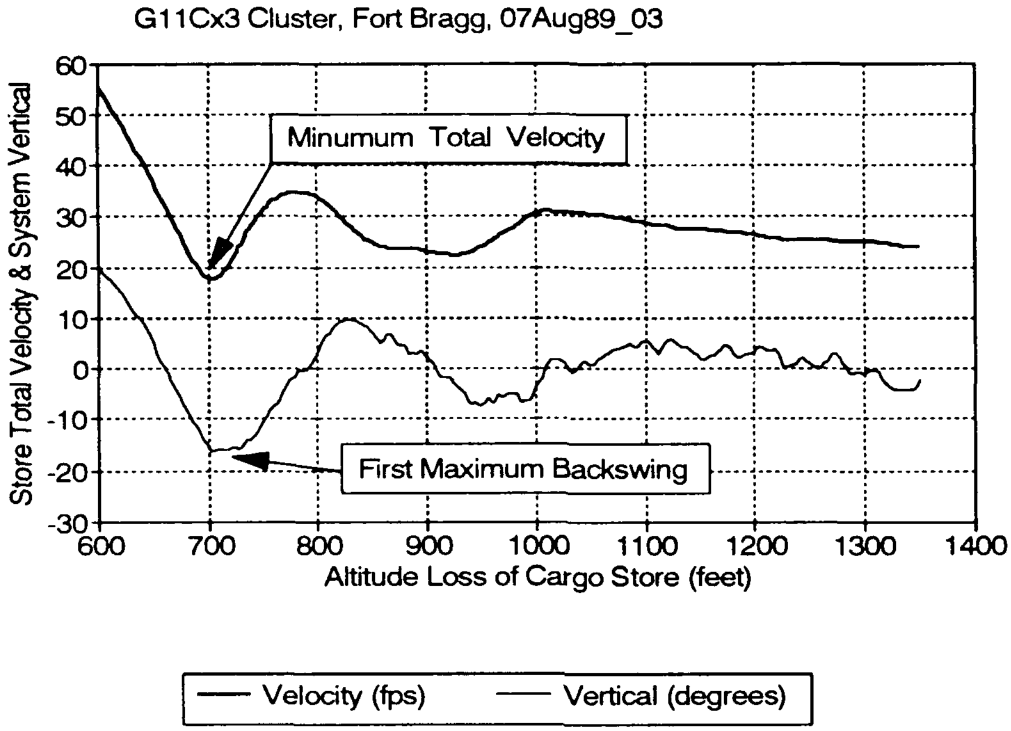

Figure 4: Total Velocity and System Vertical Angle

This correspondence between the first maximum backswing orientation of the system and the first minimum total velocity of the cargo was observed for all the systems within the G-11 family which were studied.

After the cargo reaches its first minimum total velocity (an absolute minimum for all time) it reaches its next maximum at the second vertical orientation of the system (the traditionally accepted optimum time to land cargo). The relative maximum velocity of the cargo store at the second vertical orientation of the system is rarely, if ever, exceeded during ensuing oscillations.

After the first maximum backswing orientation of the system, the total velocity of the cargo is bounded between the first minimum total velocity and the maximum which occurs at the second vertical orientation of the system.

The following graph shows this relationship for a cluster of Eight parachutes:

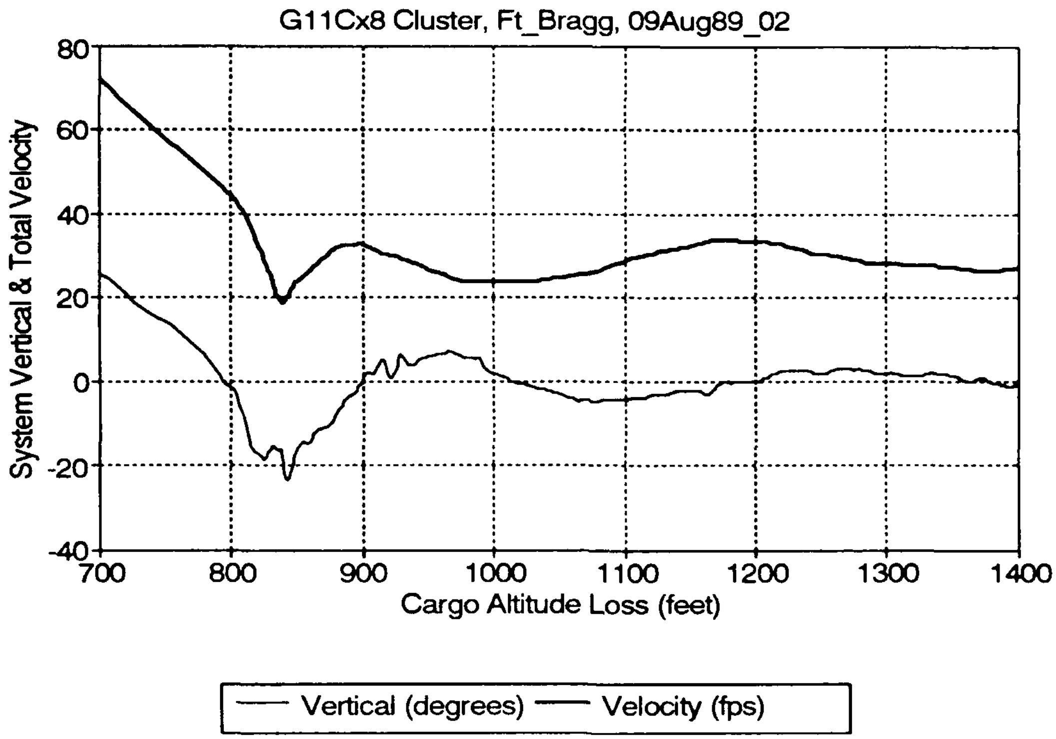

Figure 5: Total Velocity and System Vertical for Cluster of Eight

Usefulness of Equation

The calculation of the system vertical angle has great practical utility. Previous investigations of the pitching oscillations of parachutes were subject to error; largely because, in addition to measuring the location of the cargo at each moment in time, the location of the geometric center of the canopies must also be determined visually. This is a source of error which increases with the number of parachutes in a cluster. This new method of calculating the effective system vertical, in addition to being objective, also obviates the expense of measuring the location of the canopies in time. The equation should, as a matter of course, be validated as an analysis tool through experimentation.

Results

New Definitions

Based upon the ability to calculate the effective system vertical angle and the recognition that the first minimum velocity of the cargo always occurs at (or just prior) to the effective system vertical angle, the **minimum altitude** is redefined as follows:

First Minimum Total Velocity occurs when the total velocity of the cargo reaches its first minimum. From a practical point of view, the first minimum total velocity of the cargo occurs at (or just prior to) the time that the system arrives at its **first maximum backswing** orientation, as determined by application of equation (2).

Minimum Altitude is equal to the altitude loss of the center of mass of the cargo store from the time of its extraction (exit) and to the time it reaches its **first minimum total velocity.**

Determination of Altitude Loss

The altitude loss of the cargo from extraction to the **first minimum total velocity** of the cargo, determined from trajectory data acquired at Fort Bragg by the Airborne and Special Operations Test Directorate, (OPTEC) for a wide range of airdrop system configurations (1 to 8 parachutes). These values form the basis for the statistical determination of the average and standard deviation of the altitude loss for each cluster family. The corresponding time from extraction (exit) of the cargo to the first minimum total velocity of the cargo was determined in the same manner.

The altitude loss (drop) and elapsed time (drop time) from extraction to the first minimum total velocity of the cargo were determined for each configuration (cluster family). The statistical analysis for each family was undertaken by Matti Harm, Systems Management Branch. It relies heavily upon the reasonable assumption that the data used to determine the minimum altitude were obtained while testing parachute systems at Fort Bragg, NC, under weather conditions which can be considered **typical.** The variability used to determine reliability factors to be added to the mean altitude loss reflects, to some extent, the variability in weather conditions at Fort Bragg.

Sources of Error and Variability

Since the reliability factor to be added to the statistically determined mean altitude loss is based upon the variability (standard deviation) of the data, the sources of error and variability are examined.

Sources of error and variability in the estimation of the minimum altitude can be attributed to the following factors:

- Measurement Error
- System Variability
- Weather Effects

The variance observed in the data is due to the interaction of all three factors.

The first factor, measurement error, is the consequence of the methods used to acquire trajectory data at Fort Bragg.

The second factor, system variability, is dependent upon the design and operation of the airdrop system. Since system components and deployment are never exactly the same, performance variability is inherent and systemic from a statistical point of view.

The third factor, weather effects, introduces random perturbations upon the performance of each system. The variations caused by weather conditions typical of Fort Bragg are therefore embedded in the data.

Measurement Error

The trajectory (spatial position) data from Fort Bragg is obtained using optical tracking cameras. The determination of the spatial position of the cargo is subject to the resolution limitations of the cameras and the method of visually selecting the location of the center of mass of the cargo from images. It is beyond the scope of this report to analyze the precision and accuracy of spatial position data, except to state that systematic error has to some extent already been eliminated from this analysis in two ways:

- The altitude loss has been determined by subtracting the altitude of the center of mass of the cargo at the time that it reaches its first minimum total velocity, from its altitude at the time it was extracted. Subtraction eliminates constant (zeroth order) systematic error.

- First order systematic error has been eliminated from the total velocity of the cargo; since, it represents the time derivative of the spatial (position) data.

The standard practice (Fort Bragg) of using a polynomial regression algorithm to smooth the data enhances the quality of the data by reducing the random measurement error associated with visually locating the center of mass of the cargo.

Sy,tem Variability

Under identical weather conditions, the variability in the performance of parachutes will predominantly be the result of the inherent variability in the performance of the system components. The reefing line cutters, for example, if activated a second early or late, will have a significant effect upon the performance of the system. The friction between the reefing lines and the canopy skirt can slow and cause greater variability in inflation times. If two cutters are used instead of four cutters, the frictional effects can be expected to be greater because the lines will be longer, and bunching of the canopy skirt would then be more likely. In summary, the performance of each system under identical conditions can be statistically determined whereby the variability is attributed to the variability of each of its components.

Data used to determine minimum altitude was, therefore, divided according to system configuration. The various configurations studied were taken from the family of G-11 parachutes (100 foot diameter, flat circular canopy). The G-11B configurations were analyzed separately from the G-11C configurations.*

Configurations using clusters of two were analyzed separately from configurations using clusters of three parachutes. Each data set reflects the unique variability of a particular family of airdrop systems.

What is important here is that even though we may not know the variability introduced by each component.**

This variability is embedded in the data used to determine the minimum altitude for each airdrop system. The analysis is therefore considered realistic.

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* Configurations typically differ as to the reefing method and whether the canopy vent is pulled down; e.g. the G-11B configuration uses a 60 foot reefing line with 4 cutters, while the G-11C* uses a 20 foot reefing line with 2 cutters. Otherwise they are identical.

** The variability caused by system components can actually be determined through experiment by replacing one component and statistically determining the change in performance for a sufficient number of tests.

Weather Effects

A number of parameters are required to define weather:

- Humidity
- Pressure
- Precipitation
- Wind

Of these, wind has the greatest effect upon parachutes.

But not all winds are alike. Winds can vary from being smooth and predictable, to being abrupt, turbulent, and highly unpredictable. The difference between the two extremes is distinguished in a qualitative way by stating that the turbulent, highly unpredictable type contains "wind shear."

The basis for understanding these extremes in a quantitative way is to describe wind as a velocity (vector) field; whereby, not only the strength or magnitude of the air velocity may change, but also its direction. When an air mass moves at a constant velocity without deforming, its velocity can be described as uniform (isotropic) and constant (stationary) at all points in the velocity field. This is the simplest manifestation of wind.

A non-gliding parachute will always horizontally decelerate to the horizontal velocity of such an air mass, regardless of the velocity of the air mass with respect to earth. After deceleration in such a horizontal wind, the system will be described as **drifting** with respect to earth-fixed coordinates.

Wind Drift

The following graph displays the trajectory of a cargo suspended from a cluster of eight parachutes.

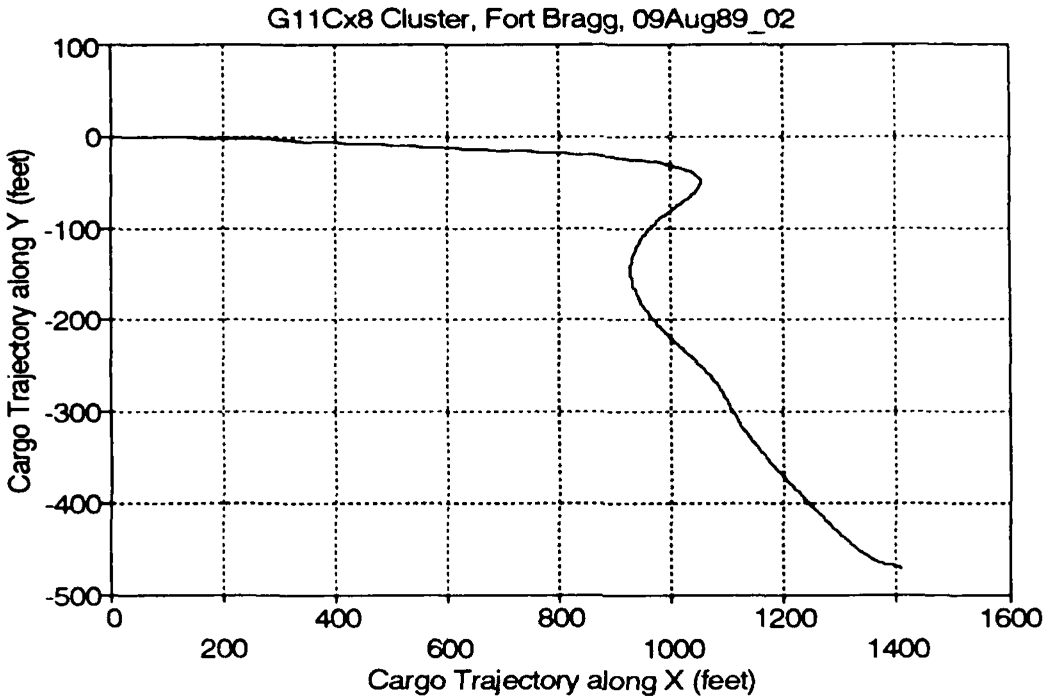

Figure 6: Wind Drift Effect

The line of flight of the aircraft is along the X-Axis. After opening shock, the cargo store can be seen to change direction abruptly and then maintain a more or less constant direction. The system is apparently falling through an air mass with a different velocity and direction than the air at the extraction altitude. By maintaining a constant heading and velocity after this abrupt change in velocity, the system can be said to be **drifting.***

An airdrop system with a lateral deviation of approximately 470 feet cannot be considered very accurate. However, when the drift effect is known, it can be used by the navigator to plan the flight so that the aircraft arrives upstream of the wind and with a certain "offset" from the intended point of landing so that the extraction of the cargo can be "scheduled" to minimize error. This planning is presently accomplished by the navigator using the procedures described in the Computed Air Release Systems Procedures (CARP).[3]
The problem of correcting for wind becomes more difficult when the air velocity field changes with altitude (anisotropic) or when it changes with time (non-stationary). Such an air velocity, (flow) field can be said to contain **wind shear.**

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* Assuming otherwise, e.g. assuming that the canopies are gliding leads to an unrealistic glide-ratio of approximately 1.0.

Wind Shear

The effect wind shear was studied, but is beyond the scope of this report. It can be safely said that an airdrop system descending through wind shear behaves in a different manner than when it descends in still air, and hence its trajectory is more difficult to predict.

Summary of Weather Effects

It has been demonstrated that airdrop systems are highly sensitive to wind conditions, exhibiting effects from both wind drift and wind shear. Of the two, wind drift is easier to understand because the parachute decelerates in the same manner as it would in still air, it just appears to be moving with respect to the earth. The effects of wind shear, on the other hand, are highly unpredictable, because as the system is falling crosswinds are constantly changing, which can affect all functional phases, from extraction until landing.

Trajectory data obtained from Fort Bragg (located in a geographically flat unsheltered area, where wind shear can be quite strong) has purposely not been adjusted to eliminate such random wind effects. This was done so that the data used to determine the average (mean) **minimum altitude** and the associated variation (standard deviation) will contain the random effects of winds at Fort Bragg. The conclusions drawn from statistical analysis of this trajectory data can therefore be considered more reasonable since data was also obtained at random, i.e. at different times throughout the year and at a location unsheltered from winds.

The discussion of sources of error and variation is motivated by a consideration for the safety of operations, primarily because the reliability factor to be applied to the mean altitude loss determined for each family of low-velocity airdrop systems is derived from the standard deviation (variability) of each trajectory data set.

This concern for safety relates to the performance of all parachutes, personnel as well as cargo. An attempt to define a safe performance envelope for personnel parachutes, e.g. during the inflation process,[4] will most surely require an understanding of wind shear effects as well.

The concern for variability also relates to the fact that present airdrop operations do not provide guidelines for flight planning to correct for wind shear.

It is the Air Force navigator who is responsible for calculating the computed air release point (CARP) from local weather reports and also responsible for making last minute corrections based upon an assessment of wind shear deduced from observations (smoke plumes, etc.) near the drop zone.

But what corrections to the derived minimums should be applied when adverse wind shears are observed during military operations?

Not enough is yet known about the effects of wind shear upon the performance of parachute systems to provide an objective correction based upon the navigator's observations.

A better understanding of the effects of wind, especially wind shear, could support further improvements in the reliability and accuracy of airdrop systems.

Conclusions

- **Minimum altitude** should be defined as the distance between the altitude of the center of mass of cargo at extraction (exit) and the altitude at which it reaches its **first minimum total velocity.**

- Application of equation (2) provides an objective method for determining the **system vertical angle** which is more accurate than previous methods, especially when the system is comprised of clusters of parachutes.

- Equation (2) indicates that the first minimum total velocity of the cargo occurs at (or just prior to) the **first maximum backswing** orientation of the system

- Using equation (2) can result in cost savings by obviating the need for a second pass of film analysis, as was previously required to analyze the system vertical.

- The determination of minimum altitude relies heavily upon the assumption that the data used to determine the minimum altitude was obtained during the testing of parachute systems under **typical** weather conditions.

- For safety reasons, the data used to determine the reliability factor to be added to the minimum altitude should not be corrected for weather effects. Perturbations introduced by weather effects should remain embedded within the data – until the effects of winds are better understood.

- One of the more significant factors affecting parachute performance appears to be **wind shear,** for which little or no research information is available. It is believed that the effects of wind shear pervade all phases of parachute performance: deployment, inflation, rotation, and oscillation.

Recommendations

- The new parachute trajectory database should be used and expanded by all airdrop engineers needing to analyze parachute trajectories.

- The equation used to calculate the effective system vertical angle should be validated through experimentation.

- A greater understanding of the effects of wind shear upon the performance of parachutes is needed to understand the performance variability and the reliability factor which is added when determining minimum altitude.

- Research into the effects of wind shear upon parachute behavior should be undertaken to support future development of airdrop systems having greater predictability, not only in terms of altitude loss, but in terms of the accuracy with which cargo can be delivered to a point.

- The accuracy of weather balloons in determining wind velocity and shear should be investigated. Improvements may be necessary to obtain more accurate wind velocity and shear data in support of research into the understanding of the non-steady behavior of parachutes as well as the safety and accuracy of the airdrop method.

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